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Review of 600–2500 kW sized wind turbines and optimization of hub height for maximum wind energy yield realization

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ABSTRACT

The percent increase in energy production with corresponding increase in hub-height for wind energy conversion system (WECS) from different manufacturers was compared in this study. It was seen that an increase of 10 m in hub-height from 40 to 50 m resulted in an increase of 3.17% in energy production for wind turbines from Nordex, while a change of 3.48% from Vestas, and so on. The overall mean increase in energy production was found to be 2.92% while changing the hub-height from 40 to 50 m. Further increase of 10 m in hub-height from 50 to 60 m, showed an increase of 7.55%, 7.90%, 7.88%, 8.25%, 8.14% and 7.75% for WECS from Nordex, Vestas, DeWind, GE, Bonus and Enercon respectively. The overall mean increase in energy production was found to be 7.91% for this change of hub-height from 50 to 60 m. Similarly, an increase of 3.02% in energy production was obtained for an additional of 10 m increase in hub-height i.e. from 70 to 80 m. On the average the maximum increase in energy production of 7.91% was obtained while changing hub-height from 50 to 60 m.

Contents

1. Introduction

Power of the wind is a pollution free, clean, inexhaustible, free and renewable source of energy. The continued rapid growth of wind power despite the financial crisis and economic downturn is testament to the inherent attractiveness of the technology, which is clean, reliable and quick to install. Wind power has become the power technology of choice a growing number of countries around the world. According to Global Wind Energy Council [1], the world's wind power capacity grew by 31% in 2009, adding 37.5 GW to bring total installations to 157.9 GW. One third of these additions were made in China, which experienced yet another year of over 100% growth. Newly added capacity of 1270 MW in India and some smaller additions in Japan, South Korea and Taiwan make Asia the biggest regional market for wind energy in 2009, with more than 14 GW of new capacity.

However, the US continues to have a comfortable lead in terms of total installed capacity. Against all expectations, the US wind energy market installed nearly 10 GW in 2009, increasing the country's installed capacity by 39% and bringing the total installed grid-connected capacity to 35 GW. Europe, which has traditionally been the world's largest market for wind energy development, continued to see strong growth, also exceeding expectations. In 2009, 10.5 GW were installed in Europe, led by Spain (2.5 GW) and Germany (1.9 GW). Italy, France and the UK all added more than 1 GW of new wind capacity each. The 158 GW of global wind

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Table 1
Technical data of Nordex wind machines used in the analysis.

Wind machine	Cut-in speed (m/s)	Cutout speed (m/s)	Rated speed (m/s)	Rated output (kW)	Hub height (m)	Rotor diameter (m)	Expected life (years)
N80/2500	4	25	14	2500	60	80	20
N90/2300	4	25	13	2300	80	90	20
S70/1500	3	25	13	1500	65	70	20
N60/1300	3	25	15	1300	60	60	20
N54/1000	4	25	14	1000	60	54	20
N50/800	3	25	15	800	50	50	20
N43/600	3	25	13.5	600	40	43	20

Table 2
Technical data of VESTAS wind machines used in the analysis.

Wind machine	Cut-in speed (m/s)	Cutout speed (m/s)	Rated speed (m/s)	Rated output (kW)	Hub height (m)	Rotor diameter (m)	Expected life (years)
V42	4	25	17	600	35, 40, 50, 55	42	20
V52	4	25	16	850	49, 55, 60, 65	52	20
V63	4.5	25	16	1500	58, 60	63	20
V80	4	25	15	2000	60, 67, 78, 100	80	20

Table 3
Technical data of GE wind machines used in the analysis.

Wind machine	Cut-in speed (m/s)	Cutout speed (m/s)	Rated speed (m/s)	Rated output (kW)	Hub height (m)	Rotor diameter (m)	Expected life (years)
GE/900s	3	25	13	900	60	55	20
GE/1.5SL	4	20	14	1500	65, 80	77	20
GE45.7	3	25	14	2300	80 to 95	94	20
GE42.7	4	25	15	2500	70 to 90	88	20

Table 4
Technical data of DeWind wind machines used in the analysis.

Wind machine	Cut-in speed (m/s)	Cutout speed (m/s)	Rated speed (m/s)	Rated output (kW)	Hub height (m)	Rotor diameter (m)	Expected life (years)
D4/48	3	22	11.5	600	40, 55, 60, 70	48	20
D6/60	3	23	11.5	1000	60, 65, 68, 91	60	20
D8/80	3	None	13.5	2000	80, 95	80	20

Table 5
Technical data of Bonus wind machines used in the analysis.

Wind machine	Cut-in speed (m/s)	Cutout speed (m/s)	Rated speed (m/s)	Rated output (kW)	Hub height (m)	Rotor diameter (m)	Expected life (years)
Bonus/44	3	25	13	600	40, 45, 50, 60	44	20
Bonus/54	3	25	15	1000	45, 50, 60	54.2	20
Bonus	3	25	15	1300	45–68	62	20

capacity in place at the end of 2009 will produce 340 TWh of clean electricity and save 204 million tons of CO_2 every year.

Wind data analysis and accurate wind energy potential assessment is critical for proper and efficient development of wind power application and is highly site dependent. Ackermann and Soder [2] provided an overview of the historical development of wind energy technology and discussed the worldwide status of grid-connected as well as stand-alone wind power generation. Moran and Sherrington [3] presented cost–benefit analysis to assess the economic feasibility of a large scale wind farm project, taking into account positive and negative externalities of generation. Herbert et al. [4] reviewed the wind resource assessment models, site selection models and aerodynamic models. The study found out that the Weibull, Rayleigh distribution and Markov chain models are suitable for prediction of wind speed at the site.

Globally, numerous studies have been reported in the literature on various aspects of wind speed and wind power characteristics. Some of these studies include Marafia and Ashour [5] for offshore/onshore wind power project development in Libya; Al-Nassar et al. [6] showed that the annual mean wind speed in Kuwait lied in the range of 3.7–5.5 m/s; Anagreh and Bataineh [7] reported wind resource assessment of the different regions of Jordan; Radics and Bartholy [8] for Hungary; Ucar and Balo [9] for Manisa, Turkey; Omer [10] for Sudan; and Sahin and Bilgili [11] studied the wind characteristics of Belen-Hatay province of Turkey using hourly wind speed records between years 2004 and 2005. Rehman et al. [12] presented the Weibull parameters for ten anemometer locations in Saudi Arabia and found that the wind speed was well represented by Weibull distribution function. Rehman and Halawani [13] presented the statistical characteristics of wind

Table 6
Technical data of Enercon wind machines used in the analysis.

Wind machine	Cut-in speed (m/s)	Cutout speed (m/s)	Rated speed (m/s)	Rated output (kW)	Hub height (m)	Rotor diameter (m)	Expected life (years)
E-40-6.44	2.5	28	12	600	46, 50, 58, 65	44	20
E-58-10.58	2.5	28	12	1000	70.5, 89	58	20
E-66-15.66	2.5	28	12	1500	67, 85, 98	66	20
E-66-18.70	2.5	28	12	1800	65, 85, 98	70	20

Table 7
Summary of wind energy production (MWh/year) from single WECS.

Manufacturer	Size of wind energy conversion system (WECS-kW)									
	600	800	850	900	1000	1300	1500	2000	2300	2500
Nordex										
40 m	1326.0	1717.92	–	–	2021.51	2569.90	3988.60	–	5611.64	4776.82
50 m	1377.9	1777.54	–	–	2068.24	2663.62	4068.64	–	5765.07	4972.98
60 m	1477.6	1918.38	–	–	2237.79	2880.49	4308.23	–	6210.01	5358.54
70 m	1542.6	2004.98	–	–	2345.97	3023.97	4458.38	–	6432.01	5630.07
80 m	1577.0	2047.26	–	–	2413.92	3098.80	4600.79	–	6622.39	5784.47
Vestas										
40 m	1234.7	–	1977.95	–	–	–	2952.01	–	4509.22	–
50 m	1278.6	–	2037.13	–	–	–	3071.85	–	4659.07	–
60 m	1385.1	–	2186.75	–	–	–	3325.71	–	5015.48	–
70 m	1446.7	–	2271.52	–	–	–	3483.77	–	5220.91	–
80 m	1498.2	–	2341.04	–	–	–	3591.92	–	5373.40	–
DeWind										
40 m	1589.6	–	–	–	2613.85	–	–	4815.18	–	–
50 m	1616.6	–	–	–	2656.21	–	–	4943.31	–	–
60 m	1741.3	–	–	–	2870.28	–	–	5331.79	–	–
70 m	1815.6	–	–	–	2974.39	–	–	5530.96	–	–
80 m	1866.1	–	–	–	3061.88	–	–	5689.26	–	–
GE										
40 m	–	–	–	2176.49	–	–	3874.27	–	5817.59	5588.79
50 m	–	–	–	2233.86	–	–	3969.33	–	5908.69	5786.53
60 m	–	–	–	2416.42	–	–	4255.13	–	6482.65	6243.89
70 m	–	–	–	2512.14	–	–	4435.76	–	6564.76	6521.14
80 m	–	–	–	2600.71	–	–	4578.24	–	6778.03	6703.99
Bonus										
40 m	1140.4	–	–	–	2179.16	2822.51	–	–	–	–
50 m	1182.4	–	–	–	2251.62	2913.10	–	–	–	–
60 m	1291.7	–	–	–	2422.52	3133.95	–	–	–	–
70 m	1358.4	–	–	–	2519.08	3257.66	–	–	–	–
80 m	1408.2	–	–	–	2593.25	3356.36	–	–	–	–
Enercon 1800 kW										
40 m	1402.2	–	–	–	2394.18	–	3193.42	3745.28	–	–
50 m	1439.3	–	–	–	2462.27	–	3318.76	3902.29	–	–
60 m	1553.6	–	–	–	2652.54	–	3580.83	4191.63	–	–
70 m	1612.3	–	–	–	2748.50	–	3735.31	4384.59	–	–
80 m	1659.3	–	–	–	2827.82	–	3836.75	4496.34	–	–

speed and diurnal variation. The autocorrelation coefficients were found to be matching with the actual diurnal variation of the hourly mean wind speed for most of the locations used in the study. Some of the other studies include Rehman et al. [14], Rehman and Aftab [15] and Rehman et al. [16].

The selection of wind machine size will depend on the existing world wide standard sizes, commercial availability, high energy yield and capacity factor, local adoptability, ease of transportation to the installation site, etc. The choice of a particular wind turbine could include the interest of the manufacturer to providing services, competitive cost, technical support during installation phase, training of the operation and maintenance staff, terms and conditions for maintenance of the wind machines and the supply of spare parts during project life time, re-powering provision of the plant after the expiry of designed life, etc.

The placement of a right turbine at the right place is very important and critical from optimal energy production point of view. The other important aspects are its rated power, cut-in-speed, transportability, life span, capital cost, corrosion resistance, harsh weather resistance, etc. Wind turbines are now available in few hundreds of kilowatt to few mega watt rated capacities and are being used successfully worldwide. A wind machines consists of a nacelle unit, a tower and blades. The nacelle unit is the main unit of the whole assembly and houses the gear box, the cooling system, generator and other control systems. To further understand the workability and other characteristics of the wind energy conversion system (WECS) a number of major manufacturers were identified, contacted and technical specifications on different sizes of the WECS were obtained.

The Kingdom of Saudi Arabia with vast open land high available winds may be a good candidate for the installation of wind electricity conversion systems. The Kingdom is proud to have 20 meteorological data collection stations, which dates back to 1970. So, a wealth of meteorological data is available for the design and planning of wind energy systems. This study utilizes wind speed data from many locations and wind turbines from different manufacturers to estimate the wind energy at different hub heights. The placement of a right turbine at the right place is very important and critical from optimal energy production point of view. The other important aspects are its rated power, cut-in-speed, transportability, life span, capital cost, corrosion resistivity, harsh weather resistance, etc.

2. Energy yield from wind machine

Energy production from single WECS was obtained from wind power curves of the wind machines and the frequency distribution of number of hours during which the wind remained in certain wind speed intervals. To perform energy calculations several wind machines with different sizes were chosen on the basis of generally used sizes in wind power sector. According to Bolinger and Wiser [17], the average size of utility-scale wind turbines installed in the U.S. was 686 kW in 2000 while it was 327 kW in 1995. In the

Table 8
Percent increase in energy production with increasing hub-height for Yanbu.

Manufacturer WECS size (kW)	Percent increase in energy with hub-height			
	40–50	50–60	60–70	70–80
Nordex				
600	3.91	7.24	4.40	2.23
800	3.47	7.92	4.51	2.11
1000	2.31	8.20	4.83	2.90
1300	3.65	8.14	4.98	2.47
1500	2.01	5.89	3.48	3.19
2300	2.73	7.72	3.57	2.96
2500	4.11	7.75	5.07	2.74
Mean (%)	3.17	7.55	4.41	2.66
Vestas				
600	3.55	8.33	4.45	3.56
850	2.99	7.34	3.88	3.06
1500	4.06	8.26	4.75	3.10
2300	3.32	7.65	4.10	2.92
Mean (%)	3.48	7.90	4.29	3.16
DeWind				
600	1.70	7.72	4.27	2.78
1000	1.62	8.05	3.63	2.94
2000	2.66	7.86	3.74	2.86
Mean (%)	1.99	7.88	3.88	2.86
GE				
900	2.64	8.17	3.96	3.53
1500	2.45	7.20	4.25	3.21
2300	1.57	9.71	1.27	3.25
2500	3.54	7.90	4.44	2.80
Mean (%)	2.55	8.25	3.48	3.20
Bonus				
600	3.68	9.24	5.17	3.67
1000	3.33	7.59	3.99	2.94
1300	3.21	7.58	3.95	3.03
Mean (%)	3.41	8.14	4.37	3.21
Enercon				
600	2.64	7.94	3.78	2.92
1000	2.84	7.73	3.62	2.89
1500	3.92	7.90	4.31	2.72
1800	4.19	7.41	4.60	2.55
Mean (%)	3.40	7.75	4.08	2.77
Overall (%)	3.00	7.91	4.09	2.98

year 2001, the average size of utility-turbines reached to 893 kW. In Europe, the trend of higher capacity wind machines has become a deciding factor in wind farm development projects due to scarcity of land. The developers are embarking on 1.5–2.5 MW size of wind machines with 80–90 m high towers. Larger wind machines produce more power and acquire less space, so they are getting popular in Europe. For energy production and plant capacity factor (PCF) analysis, wind machines of 600, 800, 850, 900, 1000, 1300, 1500, 1800, 2000, 2300 and 2500 kW sizes from manufacturers Nordex, Vestas, GE, DeWind, Bonus and Enercon were chosen.

Table 1 summarizes the technical information of wind machines of sizes 600, 800, 1000, 1300, 1500, 2300 and 2500 kW from Nordex. As seen from Table 1, the cut-in-speed of most machines is 3 m/s while the cutout speed is 25 m/s. The hub-height varies between 40 and 80 m for whole range (600–2500 kW) of wind machines listed in Table 1. The technical information on Nordex wind machines and the wind power curves were obtained from references [18–24]. The wind power curves for all the WECS from Nordex are shown in Fig. 1. The frequency distribution was obtained by constructing the wind rose using hourly average wind data at 40, 50, 60, 70 and

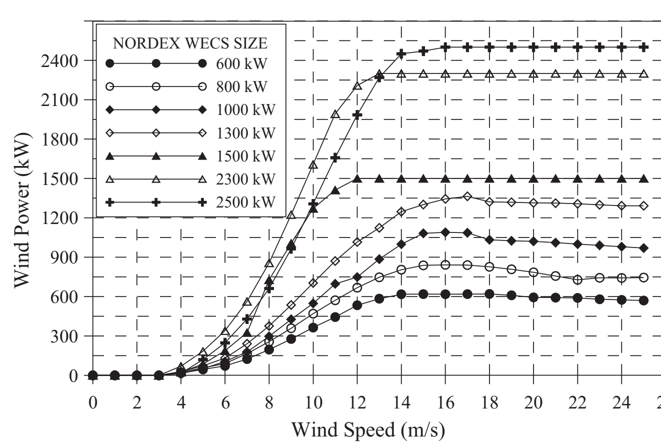


Fig. 1. Wind power curves for WECS of different sizes from Nordex.

Table 9
Plant capacity factors for wind machines of different sizes.

Manufacturer	Size of wind energy conversion system (WECS-kW)									
	600	800	850	900	1000	1300	1500	2000	2300	2500
Nordex										
40 m	25.2	24.5	–	–	23.1	22.6	30.4	–	27.9	21.8
50 m	26.2	25.4	–	–	23.6	23.4	31.0	–	28.6	22.7
60 m	28.1	27.4	–	–	25.5	25.3	32.8	–	30.8	24.5
70 m	29.3	28.6	–	–	26.8	26.6	33.9	–	31.9	25.7
80 m	30.0	29.2	–	–	27.6	27.2	35.0	–	32.9	26.4
Vestas										
40 m	23.5	–	26.6	–	–	–	22.5	–	25.7	–
50 m	24.3	–	27.4	–	–	–	23.4	–	26.6	–
60 m	26.4	–	29.4	–	–	–	25.3	–	28.6	–
70 m	27.5	–	30.5	–	–	–	26.5	–	29.8	–
80 m	28.5	–	31.4	–	–	–	27.3	–	30.7	–
DeWind										
40 m	30.2	–	–	–	29.8	–	–	27.5	–	–
50 m	30.8	–	–	–	30.3	–	–	28.2	–	–
60 m	33.1	–	–	–	32.8	–	–	30.4	–	–
70 m	34.5	–	–	–	34.0	–	–	31.6	–	–
80 m	35.5	–	–	–	35.0	–	–	32.5	–	–
GE										
40 m	–	–	–	27.6	–	–	29.5	–	28.9	25.5
50 m	–	–	–	28.3	–	–	30.2	–	29.3	26.4
60 m	–	–	–	30.6	–	–	32.4	–	32.2	28.5
70 m	–	–	–	31.9	–	–	33.8	–	32.6	29.8
80 m	–	–	–	33.0	–	–	34.8	–	33.6	30.6
Bonus										
40 m	21.7	–	–	–	24.9	24.8	–	–	–	–
50 m	22.5	–	–	–	25.7	25.6	–	–	–	–
60 m	24.6	–	–	–	27.7	27.5	–	–	–	–
70 m	25.8	–	–	–	28.8	28.6	–	–	–	–
80 m	26.8	–	–	–	29.6	29.5	–	–	–	–

80 m above the ground level. At these heights the wind speed was calculated using 1/7th wind power law given below:

$$V_2 = V_1\left(\frac{Z_2}{Z_1}\right)^{\alpha}$$

where V_1 and V_2 are the wind speed corresponding to heights Z_1 and Z_2, respectively and is the wind shear exponent and is taken as 1/7. The latitude, longitude and altitude of the data collection station were 24.2°N, 38.1°E and 1 m above mean sea level (MSL). The hourly averaged data covered a period of 14 years from 1970 to

Table 10
Energy yield (MWh/year) from wind farms of 20, 30 and 40 MW installed capacities at Yanbu at 60 m hub-height.

Manufacturer	Size of Wind Energy Conversion System (WECS – kW)▼									
▼	600	800	850	900	1000	1300	1500	2000	2300	2500
NORDEX	Energy Production From Wind Farms (MWh/Year)									
20 MW	48,761	47,960	-	-	44,756	43,207	56,007	-	55,890	42,868
30 MW	73,880	72,898	-	-	67,134	66,251	**86,165**	-	80,730	64,302
40 MW	98,999	95,919	-	-	89,512	89,295	**116,322**	-	105,570	85,737
VESTAS										
20 MW	45,708	-	52,482	-	-	-	43,234	-	45,139	-
30 MW	69,255	-	76,536	-	-	-	66,514	-	65,201	-
40 MW	92,802	-	102,777	-	-	-	89,794	-	85,263	-
DEWIND										
20 MW	**57,463**	-	-	-	**57,406**	-	-	53,318	-	-
30 MW	**87,065**	-	-	-	**86,108**	-	-	79,977	-	-
40 MW	**116,667**	-	-	-	114,811	-	-	106,636	-	-
GE										
20 MW	-	-	-	53,161	-	-	55,317	-	**58,344**	49,951
30 MW	-	-	-	79,742	-	-	85,103	-	84,274	74,927
40 MW	-	-	-	108,739	-	-	**114,889**	-	110,205	99,902
BONUS										
20 MW	42,626	-	-	-	48,450	47,009	-	-	-	-
30 MW	64,585	-	-	-	72,676	72,081	-	-	-	-
40 MW	86,544	-	-	-	96,901	97,152	-	-	-	-

Note: Green, blue and red colors indicate maximum, second maximum and third maximum energy production from wind farms of different installed capacities.

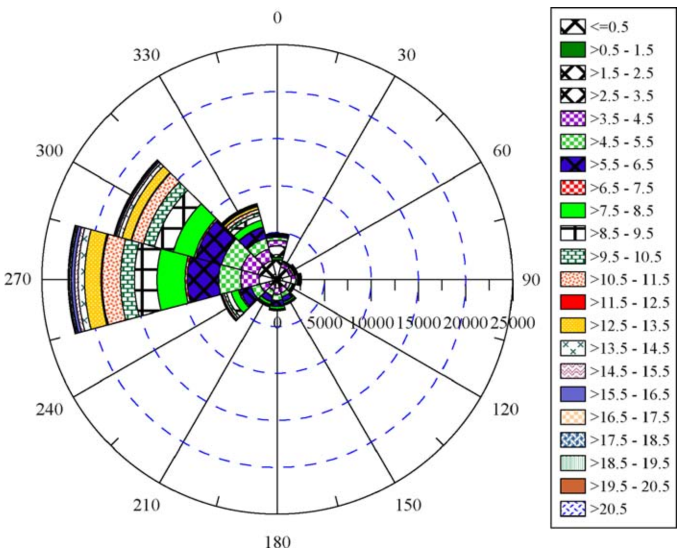


Fig. 2. Wind rose diagram of hourly mean wind speed at 40 m for Yanbu.

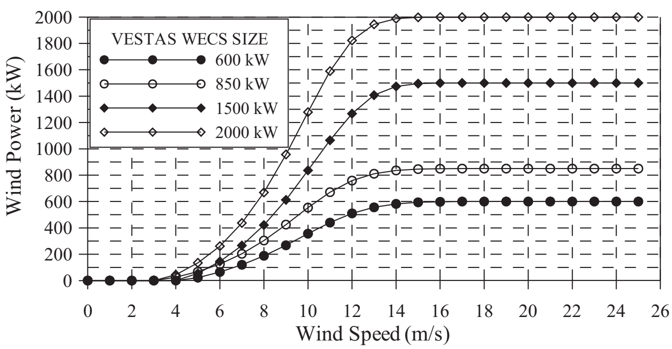


Fig. 3. Wind power curves for WECS of different sizes from Vestas.

1983 with missing data in 1976. The long-term hourly mean wind speed was 2.91 m/s at 10 m above ground level while the maximum was 6.17 m/s. The wind speed was extrapolated to higher altitude using the equation given earlier. As an example, Fig. 2 shows the wind rose diagram for wind speed at 40 m. Similar type of detailed calculations was also made for wind machines from Vestas, GE, DeWind, Bonus and Enercon. The technical information for Vestas, GE, DeWind, Bonus and Enercon WECS (Tables 2–6) and the respective wind power curves were obtained from Refs. [25–36] are shown in Figs. 3–7 and used in this study. The forth coming sections are focused on the comparison of energy production from WECS of same sizes but from different manufacturers, the effect

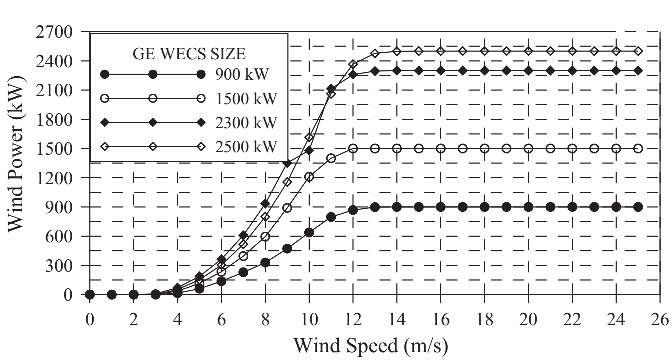


Fig. 4. Wind power curves for WECS of different sizes from GE.

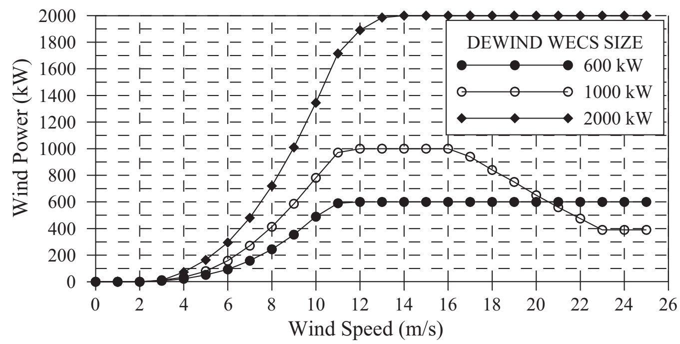


Fig. 5. Wind power curves for WECS of different sizes from DeWind.

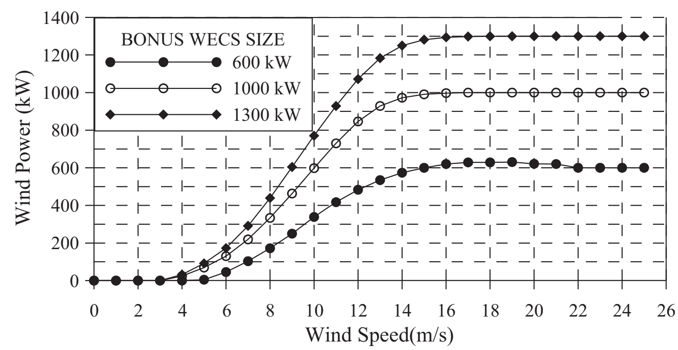


Fig. 6. Wind power curves for WECS of different sizes from Bonus.

of hub-height on energy production, plant capacity factor analysis, energy production from a wind farm of installed capacity of 20, 30 and 40 MW.

3. Comparison of annual energy yield from WECS

The annual wind energy yield (MWh/year), from different WECS is summarized in Table 7. It is observed that the maximum energy of 1589.6 MWh was obtained from DeWind machines while the minimum of 1140.4 MWh from Bonus machine of 600 kW capacity using wind speed data at 40 m. The second highest producer of wind energy of 1402.2 MWh was Enercon while Nordex stood at third place with 1326.0 MWh of electricity. Similar type of wind energy yield trends were followed at other heights, as observed from the data in Table 7. The sixth column of Table 2 shows that DeWind machine of 1000 kW rated power produces the maximum energy of 2613.85 MWh, Enercon with 2394.18 MWh of energy stood at second place and Bonus with 2179.16 MWh energy output at the third place.

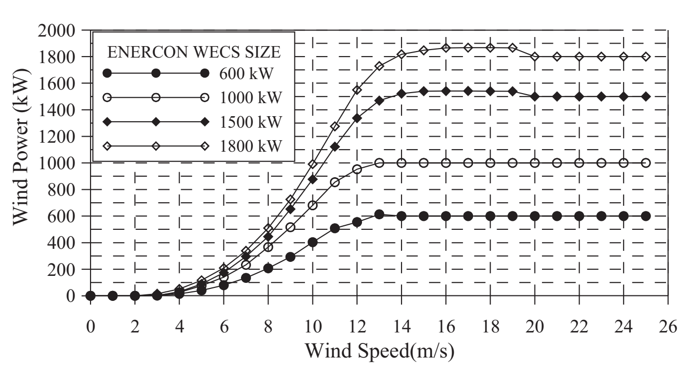


Fig. 7. Wind power curves for WECS of different sizes from Enercon.

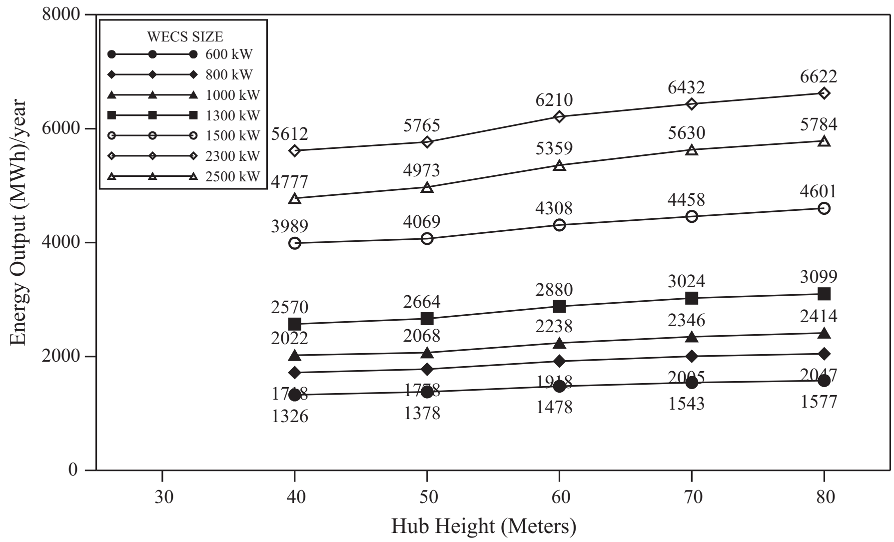


Fig. 8. Effect of hub-height on energy yield from Nordex wind machines.

The WECS with rated power of 1300 kW were available from Nordex and Bonus, as shown in Table 7, column 7. In this case the Bonus WECS performed better than the Nordex machine. The Nordex machine with 1500 kW rated power produced the maximum energy compared to WECS from Vestas, GE and Enercon. GE wind machines of rated power 2300 and 2500 kW produced maximum energy compared to others.

4. Effect of hub-height on energy yield

In order to study the effect of hub-height on energy production, the wind power curves for individual wind machines and wind duration data in different wind speed bins and at different heights was used. To obtain the wind duration or wind speed frequency distribution at different heights, the wind speed data at different heights was calculated using 1/7 wind power law. For this analysis, hourly average values of wind speed for Yanbu were used for a period of 14 years between 1970 and 1983. The energy yield from different WECS at 40, 50, 60, 70 and 80 m hub-heights, tabulated in Table 7, is shown graphically for wind turbines from Nordex in Fig. 8. It is clear that taller towers lead to increased energy yield.

Table 8 summarizes the percent increase in energy production due to increase in hub-height for all the WECS from chosen manufacturers. This table also includes the mean values of percent increase in energy yield for each hub-height change. As seen from Fig. 9, a change of hub-height from 40 to 50 m causes an increase of 3.17% in energy yield from Nordex, while a change of 3.48% from Vestas and so on. The minimum increase of 1.99% was noticed from

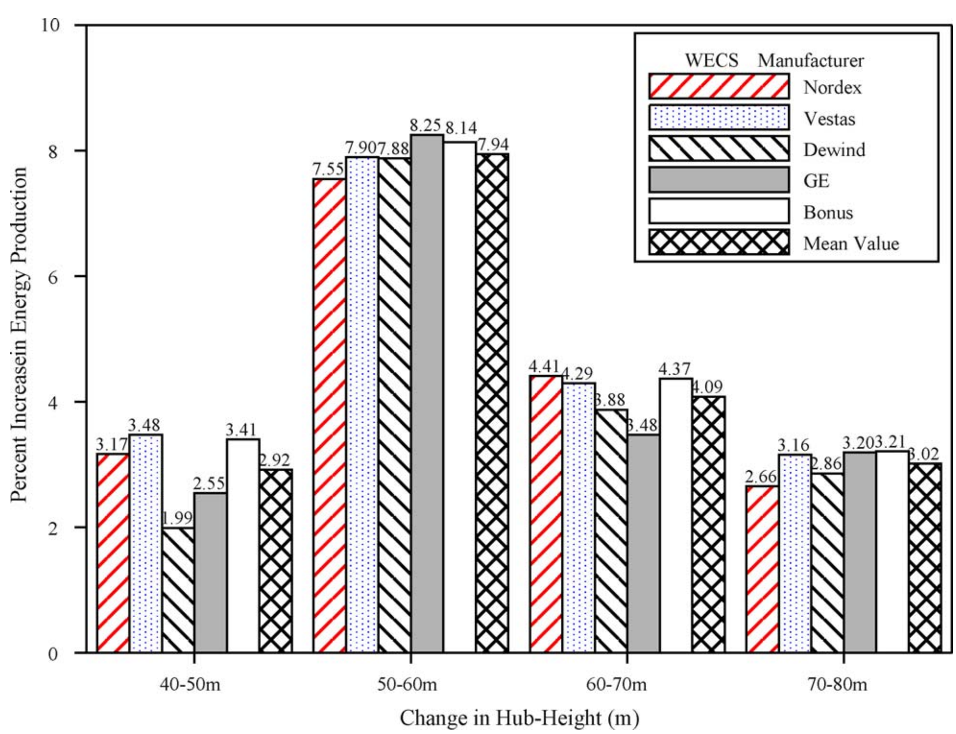


Fig. 9. Comparison of percent increase in energy yield with increase in hub-height.

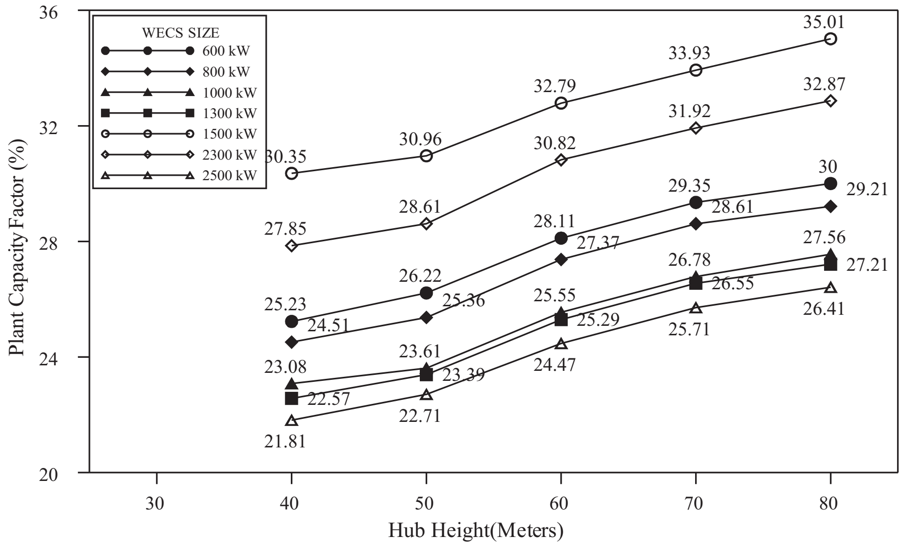


Fig. 10. Effect of hub-height on plant capacity factor for Nordex wind machines.

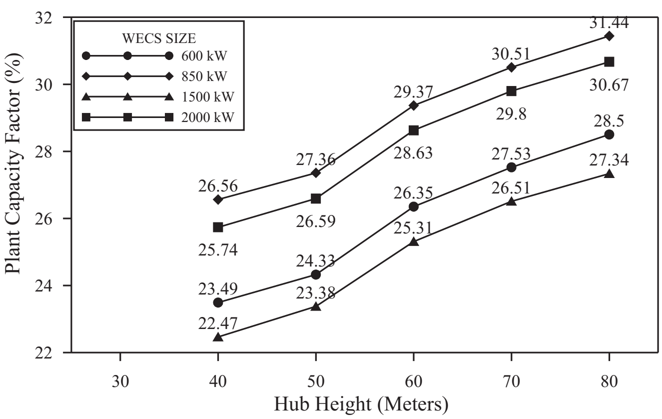


Fig. 11. Effect of hub-height on plant capacity factor for Vestas wind machines.

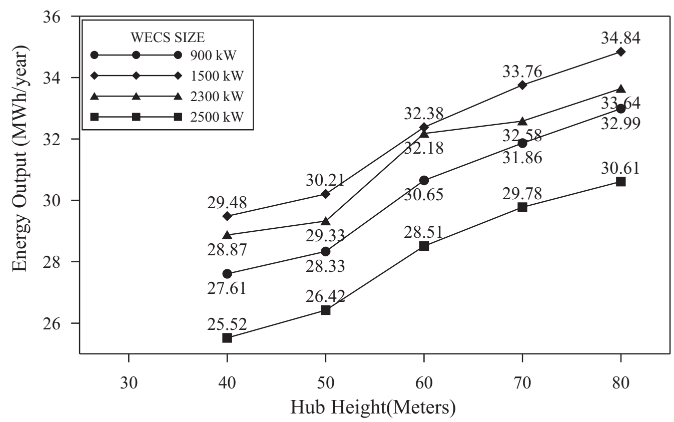


Fig. 13. Effect of hub-height on plant capacity factor for GE wind machines.

DeWind, for a change in hub-height from 40 to 50 m. The overall mean increase in energy yield was found to be 2.92% while changing the hub-height from 40 to 50 m.

Further increase of 10 m in hub-height from 50 to 60 m, showed an increase of 7.55%, 7.90%, 7.88%, 8.25%, 8.14% and 7.75 for WECS from Nordex, Vestas, DeWind, GE, Bonus and Enercon respectively, as shown in Fig. 9. The maximum increase of 8.25% was obtained from GE machines while next higher from Bonus. The overall mean increase was found to be 7.91% for this change of hub-height from 50 to 60 m. An overall mean increase of 4.09% was obtained when the hub-height was changed form 60 to 70 m. Similarly, an increase of 3.02% in energy production was obtained for an additional of 10 m increase in hub-height i.e. from 70 to 80 m.

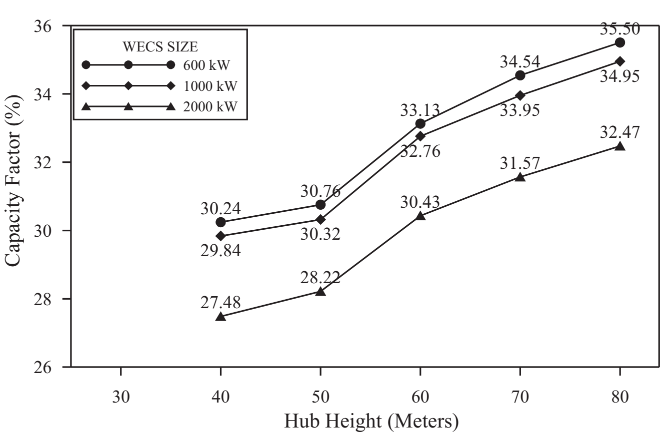


Fig. 12. Effect of hub-height on plant capacity factor for DeWind wind machines.

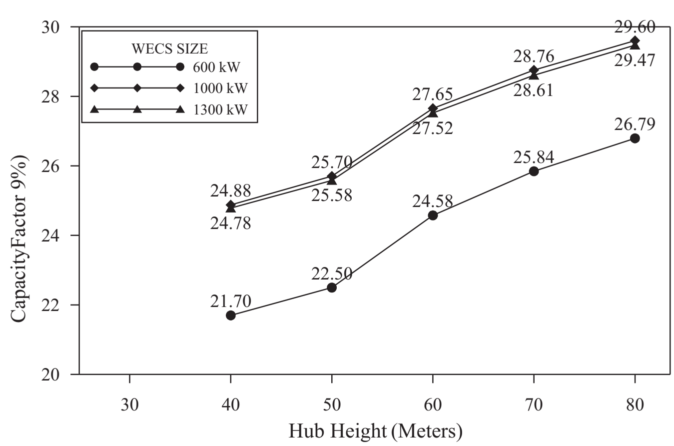


Fig. 14. Effect of hub-height on plant capacity factor for Bonus wind machines.

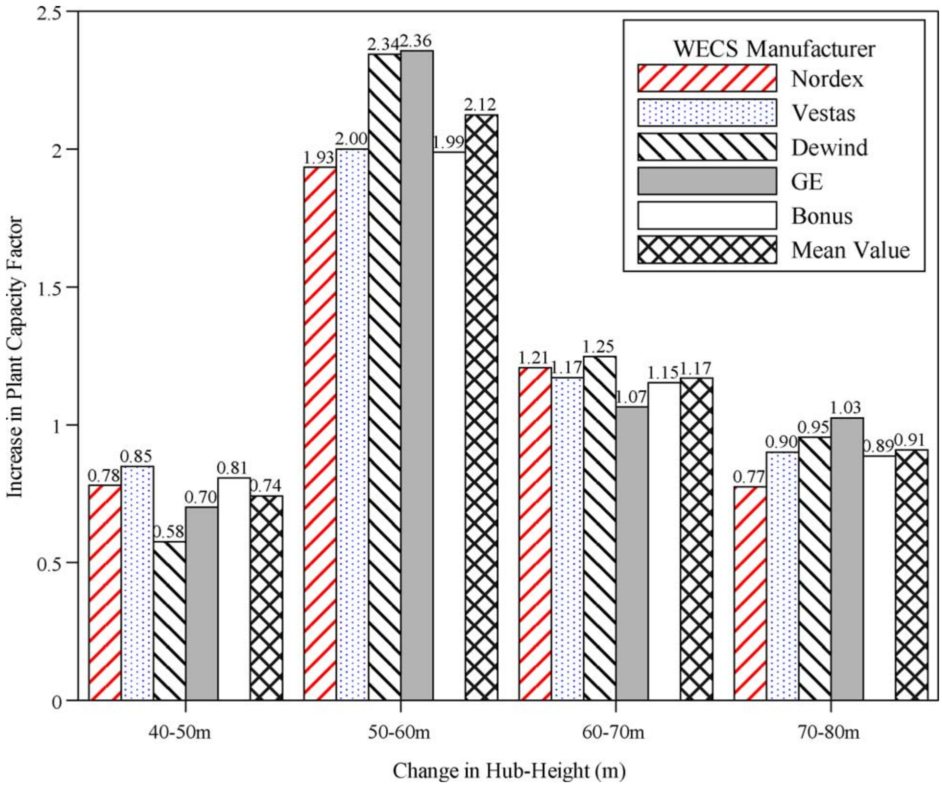


Fig. 15. Comparison of increase in plant capacity factor due to increase in hub-height for WECS from different manufacturers.

5. Plant capacity factor analysis

The plant capacity factor is a measure of the actual energy production compared to the rated power of a wind energy conversion system (WECS). Larger the PCF the better is the wind energy conversion system. The PCF generally varies from 25% to 45%. The PCF is calculated by dividing the actual energy production by the rated capacity of the WECS and number of hours in a year i.e. 8760. For plant capacity factor analysis, wind machines of 600, 800, 850, 900, 1000, 1300, 1500, 2000, 2300 and 2500 kW sizes were chosen from different manufacturers. The capacity factors calculated for all the WECS under investigation are summarized in Table 9.

While comparing the PCF for 600 kW WECS, the DeWind machine was found to attain the maximum PCF of 30.2% at 40 m hub-height and the Nordex machine the next highest PCF of 25.2%. The Vestas machine was placed at third place with PCF of 23.5% while Bonus stood at fourth place with PCF of 21.7%. The DeWind machine of 1000 kW rated power attained the maximum PCF of 29.8% while Bonus with 24.9% and Nordex with 23.1% PCF were placed at second and third place, respectively. The Nordex 1500 kW

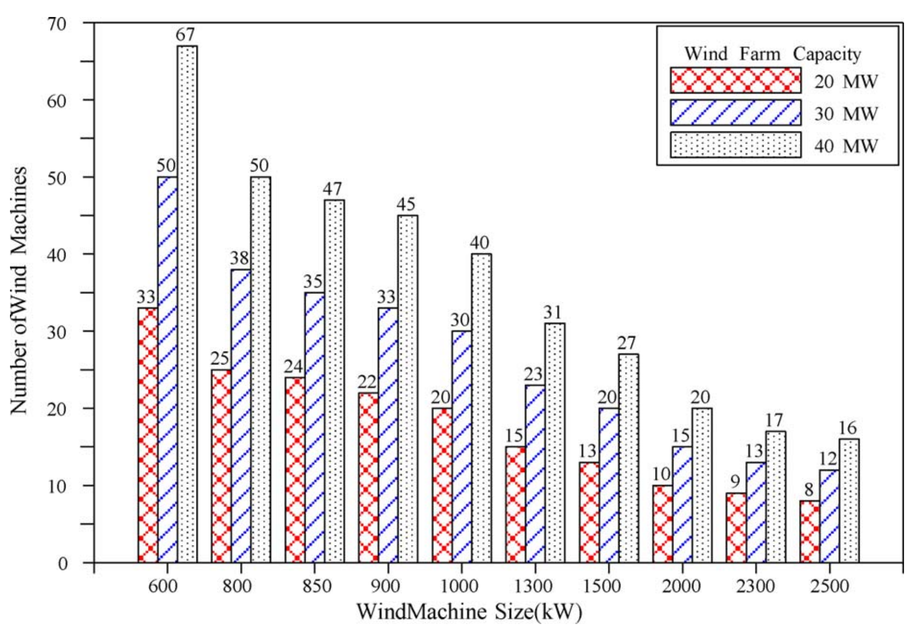


Fig. 16. Number of WECS needed for wind farms of 20, 30 and 40 MW capacities.

machine performed the best with PCF of 30.4% while GE and Vestas stood at second and third place with PCF of 29.5 and 22.5%, respectively. The GE wind machine of 2300 kW rated power performed best with PCF of 28.9%, Nordex next best with PCF of 27.9% and next best was the Vestas machine with PCF of 25.7%.

The effect of increase in hub-height on PCF is shown in Figs. 10–14 for Nordex, Vestas, DeWind, GE and Bonus machines, respectively. It is clearly understood from these figures that the PCF increases with height. The change in PCF for WECS from different manufacturers is also compared in Fig. 15. As seen from Fig. 15, the highest mean change in PCF of 0.85% was observed for WECS from Vestas while the next highest mean change of 0.81% for Bonus machines. In this class (40–50 m) of hub-height change, an overall mean increase of 0.74% in PCF was noticed. For an increase of hub-height from 50 to 60 m, a maximum mean increase of 2.36% was noticed for GE machines while the mean minimum of 1.93% for WECS from Nordex. The DeWind machines showed to be the second best with a mean increase of 2.34% in PCF and Vestas with 2.0% increase, the third best. In case of increase of hub-height from 60 to 70 m, a maximum of 1.25% change in PCF was noticed for DeWind machines while a minimum of 1.07% for GE machines. In this class of hub-height change, an overall of 1.17% increase in PCF was observed. For further increase of hub-height from 70 to 80 m, an overall of 0.91% increase in PCF was found.

6. Energy yield from wind farms

To further study the energy production for WECS from different manufacturers, wind farms of 20, 30 and 40 MW installed capacities were analyzed. The numbers of wind machines shown in Fig. 16 were approximated to nearest whole numbers wherever found in fractions. The energy produced using different sizes of wind machines for three wind farms for a hub-height of 60 m is summarized in Table 10. It is observed from this table that from 20 MW wind farm the maximum energy of 58,344 MWh/year could be produced by 9 of GE machines of 2300 kW rated power at Yanbu. The DeWind machines of 600 kW rated power produced 57,463 MWh of electricity while 1000 kW rated power WECS, from the same manufacturer, produced 57,406 MWh. For wind farms of 30 and 40 MW installed capacities, WECS of 600 kW rated power from DeWind produced the maximum electricity of 87,065 and 116,667 MWh each year on an average, respectively. The Nordex wind machines of 1500 kW rated power produced 86,165 and 116,322 MWh of electricity from wind farms of 30 and 40 MW installed capacities, respectively.

7. Conclusions and recommendations

Based on hub-height effect on energy production, it is recommended that a maximum of 60 m of hub-height should be used for wind farm development. The maximum increase of about 8% was obtained for a change of hub-height from 50 to 60 m while further increase in hub-height from 60 to 70 m produced only 4% more of electricity. The increase in energy production was found to be only 3% for further increase of 10 m in hub-height. Based on the energy production from single wind machine, the following is the rating of different sizes of WECS according to the manufacturer:

WECS Size	First	Second	Third	Fourth
600 kW	DeWind	Enercon	Nordex	Vestas
1000 kW	DeWind	Enercon	Bonus	Nordex
1500 kW	Nordex	GE	Enercon	Vestas
2300 kW	GE	Nordex	Vestas	–
2500 kW	GE	Nordex	–	–

The plant capacity analysis showed that a maximum increase of 2.12% in PCF was found when increasing the hub-height from 50 to 60 m. In the case of change of the hub-heights from 40 to 50 and 70 to 80 m the increase in PCF was less than 1% and in case of increase from 60 to 70 m the increase in PCF was a little more than 1%. The effect of hub-height on PCF matches with the hub-height effect on energy production presented in the previous sub-section. Hence it is recommended to install the wind machines at 60 m hub-height to obtain the optimal PCF.

Whereas energy yield from wind farms is concerned, 600 kW machines from DeWind performed the best while Nordex machines the next best. Vestas machines were placed at number three while Bonus at number four. The wind machines of 850 kW from Vestas and 900 kW from GE produced almost same amount of energy for all the three sizes of wind farms considered here. The DeWind machines of 1000 kW size produced the maximum electricity compared to wind machines from Nordex and Bonus.

It is recommended that the same exercise must be repeated for wind turbines of multi-mega watt sizes for optimal energy output in Saudi Arabian wind conditions which will provide a guide lines for the potential sites having similar type of wind conditions in the neighboring states. Moreover, for realistic and more accurate estimates of energy and thereof plant capacity factors, wind measurements at different heights must be used to facilitate accurate estimation of wind speed at hub-height.

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